A LOW-COST, HIGH-RELIABILITY FEMTOSECOND LASER TIMING SYSTEM FOR LCLS*

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Abstract

LCLS has developed a low-cost, high-reliability radio-frequency-based ("RF") locking system which provides phase locking with sub-25-femtosecond jitter for the injector and experiment laser systems. This system does not add significantly to the X-ray timing jitter from the accelerator RF distribution. The system uses heterodyne RF locking at 3808 MHz with an I/Q vector phase shifter and variable event receiver triggers to control the timing of the emission of the amplified laser pulse. Controls software provides full automation with a single process variable to control the laser timing over a 600 microsecond range with up to 4 femtosecond resolution, as well as online diagnostics and automatic error correction and recovery. The performance of this new locking system is sufficient for experiments with higher-precision timing needs that use an X-ray/optical cross-correlator to record relative photon arrival times.

LASER TIMING REQUIREMENTS

Lasers in the LCLS experiment hutches require sub-picosecond timing relative to the X-ray beam, originating as an electron beam from the SLAC linear particle accelerator ("linac"). The LCLS X-ray beam operates at a maximum repetition rate of 120 Hz and has a pulse-to-pulse timing jitter of approximately 60 fs RMS [1]. The relative timing of the laser and X-rays is measured in the experimental chamber by an X-ray/optical cross-correlator with approximately 10 fs resolution [2]. This cross-correlator is used to order the experimental data based on relative X-ray and laser arrival time. Any laser locking system must not substantially add to the total uncorrected experiment timing jitter. This corresponds to a target timing jitter of less than 75 fs RMS. The need to improve locking system jitter at LCLS was originally identified by Glownia *et al.* [3].

The cross-correlators used at LCLS include an optical delay stage to allow for high resolution timing measurements over a wide range of laser/X-ray time delays. The measurement range of the cross-correlator itself is approximately 1 picosecond. The timing jitter, drift, and the accuracy of laser time delay changes are required to keep the laser timed within that range, so that the cross-correlator is able to return good shot-to-shot timing data.

The range of timing scans required for experiments vary from sub-picosecond to 600 microseconds. The laser system timing needs to be adjustable over that range without additional user intervention or expert knowledge.

TIMING SYSTEM ARCHITECTURE

X-ray pulse timing is determined by the electron beam timing, which is in turn controlled by the RF fields in the accelerator cavities. The accelerator RF sources are locked to a 476 MHz RF coaxial cable phase distribution system ("RF reference"). This reference is re-stabilized to the electron beam with each shot using electron arrival time measured at RF phase cavities (Fig. 1) in the LCLS undulator hall [1]. The RF reference is then transmitted through a stabilized coaxial cable to the experiment hutches, where it is used as a phase reference for the laser locking systems described in this text.

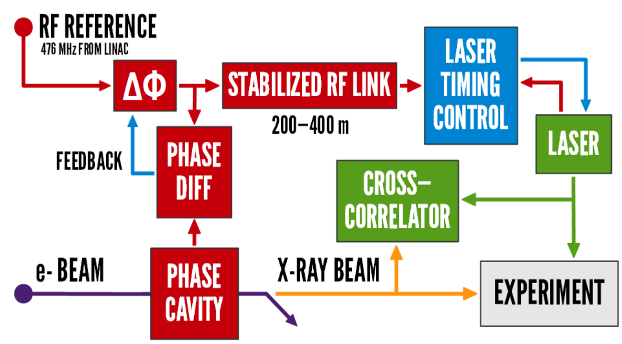

Figure 1: Laser timing system overview.

LASER TIME CONTROL

The experiment laser systems use a mode-locked Ti:sapphire laser oscillator which feeds a regenerative amplifier ("regen"). In some systems, a multipass amplifier is also used, however, the principle of operation remains the same.

The mode-locked laser oscillator (Fig. 2) operates at 68 MHz, 1/7th of the 476 MHz RF reference frequency. A commercial regenerative amplifier just after the oscillator is designed to accept an external trigger input: upon triggering, the regen selects and amplifies the next pulse from the mode-locked laser. A similar system also triggers any multipass amplifiers used downstream of the regen.

A frequency counter continuously measures the mode-locked laser cavity frequency. Controls software moves a stepper motor to coarsely control the cavity length to within 1 Hz of 68 MHz.

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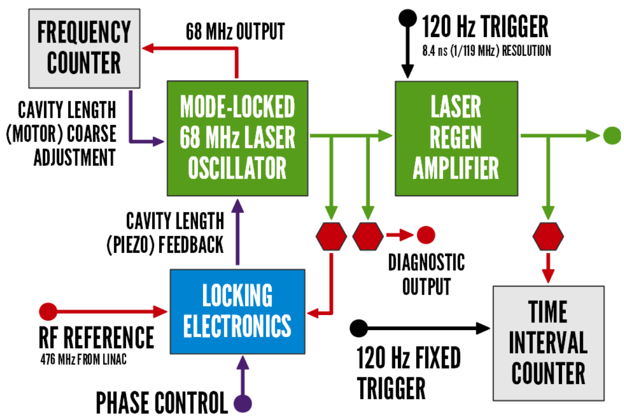

Figure 2: Basic laser timing control.

Phase locking electronics compare the phase of a photodetector on the mode-locked laser output with the accelerator reference and adjust a piezoelectrically-driven mirror ("piezo actuator") to finely control the cavity length in a phase-locked loop.

The regenerative amplifier is triggered by an event receiver connected to the LCLS event timing system. This event system uses a 119 MHz base clock (1/4 of the 476 MHz RF reference) which allows trigger outputs to be set with 8.4 nanosecond resolution.

If the phase of the mode-locked laser is adjusted by more than one cycle of 119 MHz, the regen will jump to selecting a pulse on the next 68 MHz cycle of the mode-locked laser ("regen jump"). At initial timing system setup and calibration, the output of a time interval counter (Fig. 2) is used to determine when these regen jumps occur, by sweeping the phase control while monitoring the output timing relative to a fixed trigger. This information is then used to determine how to manipulate the timing of the regenerative amplifier trigger and the 68 MHz mode-locked laser phase to obtain the desired output timing.

Because the phase locking of the mode-locked laser is performed at 3808 MHz (8×476 MHz, or 56×68 MHz), it is possible for the laser timing to jump by ~262 ps (1/3808 MHz) periods. The time interval counter is also used to detect such jumps ("bucket jumps"), which are corrected automatically by software adjustment of the locking phase and regen trigger.

OPERATING MODES

Calibration

Normally, calibration is only performed at initial installation, or after a hardware change.

The 3808 MHz vector phase shifter is dialed through approximately 30 nanoseconds of phase shift while the time interval counter reading is recorded. This determines the points in the phase shift at which regen jumps occur. The measured timing is then fit to a sawtooth curve to determine the correct settings for the regen trigger and phase shifter for normal locked operation. Both the 3808 MHz phase locking frequency, as well as the 119 MHz event timing system base clock from which the 120Hz event triggers are driven, are directly derived from the 476 MHz RF reference. This makes the time interval counter measurement more robust, as any jitter in the RF reference affects both the "start" and "stop" edges for the counter equally.

Unlocked Frequency Search

When the laser is unlocked, its free-running frequency is set by a stepper motor which coarsely controls the length of its mode-locked oscillator cavity. In this operating mode, a frequency counter measurement is used to drive a software feedback loop which moves the cavity length motor to adjust the cavity frequency to within 1 Hz of 68 MHz. The accelerator frequency and the reference for the frequency counter are each clocked by 10 MHz rubidium (Rb) references with < 1e-9 stability, making the frequency search process accurate and repeatable.

Normal Locked Operation

During normal operation, the oscillator is phase-locked to the RF reference at 3808 MHz. Timing changes are made by shifting the phase of the 3808 MHz RF and, where necessary, changing the trigger delay for the regenerative amplifier in 8.4 ns (1/119 MHz) steps to avoid regen jumps while shifting phase.

The feedback voltage on the piezo cavity length actuator for the mode-locked laser is monitored. If that voltage exceeds a set range, indicating that the piezo actuator is nearing the edge of its travel range, the cavity length control stepper motor is adjusted to allow the piezo actuator to be centered within its range of movement. This control is important to avoid saturating the piezo amplifier.

If the locking system loses phase lock, a hardware reset in the feedback circuitry will attempt to re-establish lock.

The phase lock error signal and the frequency counter are monitored in software to determine if the locking system has both lost lock and failed to recover. In this case, the system will switch back "unlocked frequency search" mode.

Bucket Jump Correction

If the phase locking of the mode-locked laser oscillator is disturbed, it can briefly lose lock and then re-lock to the 3808 MHz, sometimes ending up at an overall different time relative to the X-ray—a jump of one or more 3808 cycles, referred to as a "bucket jump". This is uncommon, occurring on average less than once per day. However, it needs to be detected and corrected when it occurs.

In normal locked operation, the time interval counter is used to monitor the delay of the regen optical output relative to a fixed trigger. If a timing jump that is close to

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an integer multiple of ~262 ps (1/3808 MHz) is detected, then the 3808 MHz phase shifter is directed to move by a corresponding integer number of cycles, returning the laser to the correct timing.

Note that because the time interval counter has a noise of ~20 ps, it is only used to detect bucket jumps (that are multiples of ~262 ps). Bucket jumps are corrected by adjusting the 3808 MHz vector phase shifter, which has a resolution of up to 4 fs and noise of a few femtoseconds RMS.

LASER PHASE DETECTION

The laser-RF phase detection system measures the relative timing of the mode-locked laser pulses and the 476 MHz linac RF reference. A high-bandwidth (10 GHz) photodiode converts the 68 MHz train of femtosecond laser pulses into a series of electrical pulses. A narrow bandpass filter then selects the 56th harmonic at 3808 MHz.

In parallel, the 476 MHz reference is multiplied in diode frequency multipliers to 3808 MHz, then shifted in phase by a software-controlled I/Q vector phase shifter. This output from the phase shifter, and the laser signal of the same frequency, are both downmixed against a 3807.75 MHz local oscillator to 250 kHz intermediate frequencies ("IF").

A higher frequency than 476 MHz was chosen for a phase detection frequency in order to reduce the dynamic range of the phase detector. Power of 2 harmonics are simple to generate with ×2 multipliers, and 3808 MHz was the highest power of two harmonic of 476 MHz that did not have a reduced response due to limited photodetector bandwidth, and which could easily be processed with conventional printed circuit board ("PCB") electronics and fabrication techniques.

The 250 kHz IF signals are compared in phase using a precision analog multiplier operating as a mixer. The phase error output is then used as the input error term in a phase-locked loop ("PLL") which controls the cavity length piezo actuator.

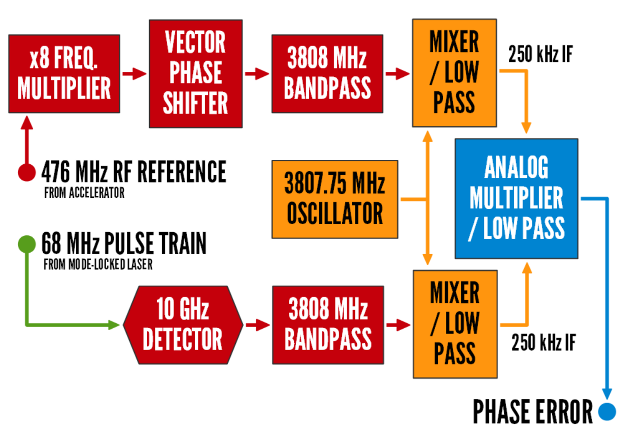

Figure 3: Laser phase detection.

LASER PHASE FEEDBACK

The laser phase locking system operates as a PLL where the output of the phase detector is used to control the frequency of the laser. An op-amp-based feedback loop with infinite gain at DC, and a second-order roll-off is used as described in Brennan [4]. If the feedback output saturates, the loop integrator capacitor is shorted by an analog switch, which resets the loop and allows the laser to re-lock.

The overall loop gain is adjustable with an analog-voltage-based gain control. The loop bandwidth is set in hardware by the resistors and capacitors in the feedback loops. Loop bandwidths between 1 kHz and 4 kHz are used depending on the dynamic response of each laser installation.

HARDWARE DESIGN

The timing system hardware is constructed from a set of independent modules to allow for easy upgrades and maintenance. These modules are also used for other RF systems at SLAC, and are based on the Stanford Research Systems ("SRS") "Small Instrumentation Module" platform ("SIM900"). The SIM900's ±5 V and ±15 V power supplies are used extensively, however, its built-in RS-232 communication is not.

The custom locking electronics are fabricated using surface mount components on inexpensive FR-4 PCB substrate (Fig. 4). This combination provides good performance at the desired 3808 MHz RF frequency at a much lower price point compared to PTFE substrate.

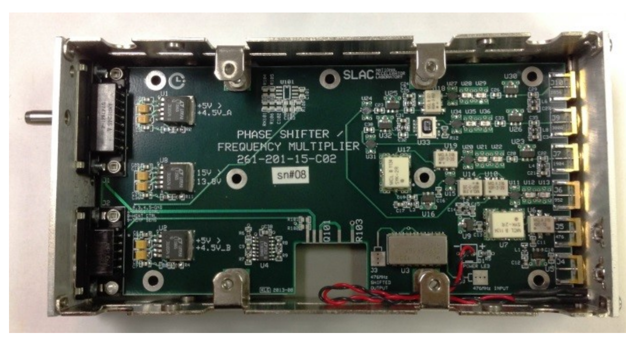

Figure 4: Frequency Multiplier PCB mounted in SRS SIM9B1 enclosure.

The full SIM900 instrumentation crate (Fig. 5, center) contains:

- Frequency Multiplier: Multiplies the 476 MHz RF reference from the accelerator ×8 to obtain a 3808 MHz reference.
- Phase Shifter: Adjusts the phase of the 3808 MHz reference signal based on two analog input voltages using an I/Q vector modulator.
- Phase Controller: Generates the analog-voltage-based I/Q vector to drive the phase shifter. Accepts commands from governing software to shift phase by fractions of the I/Q circle. Uses stepper motor

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controller firmware to provide a trapezoidal velocity profile to the phase shift, and is capable of moves of > 1e5 cycles of displacement (34 μs at 3808 MHz) at a slew rate of ~1 ms/s with ~16 fs typical resolution.

- Laser Receiver: Selects the 3808 MHz harmonic from the 68 MHz pulse train from the laser detector, and downmixes it to a 250 kHz IF. The 3808 MHz reference from the frequency multiplier is processed in the same way along a parallel path with identical components.
- Phase Detector: Compares the phases of the two 250 kHz IF signals with a precision analog multiplier (Analog Devices AD734) operating as a mixer.
- PLL: Provides the lead / lag feedback for locking the laser loop. The loop parameters are programmed by resistors and capacitors on an externally-swappable daughter-card.
- Laser Interface: Contains photodiode signal conditioning circuitry used for diagnostics.

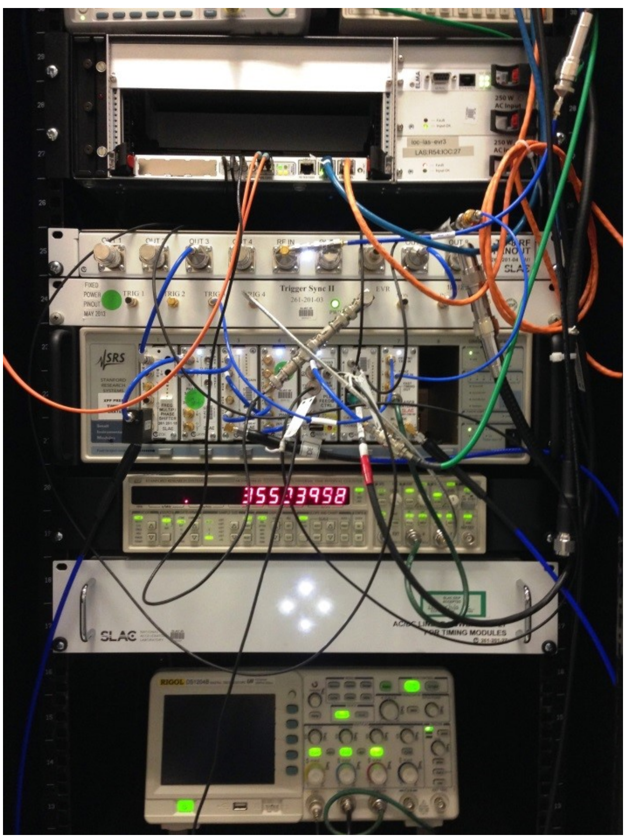

Figure 5: Full laser locking system inside rack enclosure.

The locking electronics within the SIM900 crate are further assisted by a trigger resynchronization module (Fig. 5, above SIM900) which uses the 476 MHz linac RF reference to reduce jitter on trigger signals originating from the LCLS event timing system.

Hardware Cost

The per-laser total cost of the new LCLS locking system hardware, including all off-the-shelf-components, is approximately US$40,000. This is very cost-competitive with commercial locking systems, with the additional benefit of modularity and flexibility in setup/upgrading.

SOFTWARE DESIGN

The entirety of the controls for the locking hardware system are exposed through process variables ("PV") in the LCLS installation of the Experimental Physics and Industrial Control System ("EPICS"). A layer of EPICS-based software interprets and archives system data and runs the slow loops governing the movement of the oscillator cavity length coarse adjustment motor.

Running on top of the EPICS code is a Python command & control script which consumes locking system data as well as user input from EPICS channel access ("CA"). This program coordinates movement of the event triggers and of the phase controller in the locking system crate to achieve the desired timing, based on the desired laser delay as requested by the user.

The command & control program also monitors timing data for anomalies such as bucket jumps, or other indications that the system cannot operate as designed, for example, if a photodiode becomes misaligned. Users are alerted through output EPICS PVs, and if necessary, the script disables locking system operation pending check-out and calibration.

Both EPICS and Python are open source frameworks, making the software for the locking system portable without the need for commercial licensing of any software tools.

LOCKING SYSTEM PERFORMANCE

The noise performance of the LCLS laser locking system was measured using an Agilent E5052 signal source analyzer (Fig. 6).

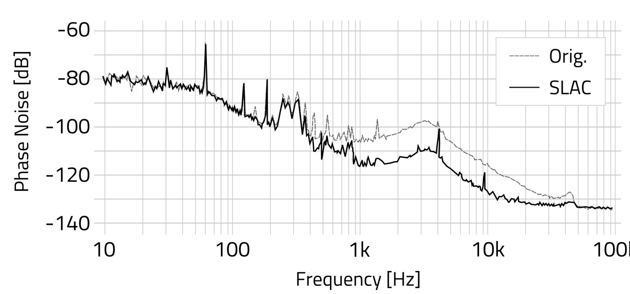

Figure 6: Trace of Agilent E5052 phase noise measurement of LCLS locking system.

When compared to the original fiber-based LCLS laser timing system [5-6], phase noise between 1 kHz and 10 kHz is improved by more than 10 dB. This results in an RMS laser / RF reference timing jitter of ~25 fs between 100 Hz and 10 kHz. Below 100 Hz, phase noise is dominated by the noise of the linac RF reference. Future efforts to reduce jitter will require improvements to the RF

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reference, however, the performance of the system in its current state is sufficient to fall well within the 1-picosecond-wide arrival time window of the X-ray/optical cross-correlator.

Drift of the RF-based locking system has been measured at less than 1 ps/day. This is suboptimal when compared to a fiber-based system, and future upgrade paths to the LCLS laser locking system include drift correction using a parallel fiber distribution system.

As of the writing of this text, the new locking system has been operating for a cumulative total of 57 system-months with only a single hardware failure, and no major downtime. When problems occur, they are straightforward to address due to the modularity inherent in the design of the locking system, and easy to debug using the online diagnostics as well as numerous external RF connections on the system crate itself.

CONCLUSION

LCLS has created a low-cost, modular, RF-based laser locking system. The cost and performance of this custom system are very competitive with commercial locking solutions. The modularity of the system makes it easily repairable and upgradable. The software control for the system runs on open source frameworks and does not depend on commercial code.

The resulting laser timing jitter of ~25 fs RMS, when combined with the X-ray timing jitter of ~60 fs RMS, ensures that the optical and X-ray pulses arrive within the 1 ps window needed for the cross-correlator, which gives users shot-to-shot timing offsets used to order data during analysis.

The new system has also met reliability expectations with only one hardware failure in 57 system-months of operation.

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The Linac Coherent Light Source is a U.S. Department of Energy Office of Science-funded facility located at SLAC National Accelerator Laboratory. LCLS is the world's first hard X-ray free-electron laser, allowing researchers to see atomic-scale detail on ultrafast timescales. The LCLS enables groundbreaking research in physics, chemistry, structural biology, energy science and many other diverse fields.

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